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# Thermal Comfort in High-rise Urban Environments in Singapore

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**Abstract**

Outdoor thermal comfort in urban spaces is an important indicator of the quality of life in urban environment. This paper attempts to investigate outdoor thermal comfort in an urban street surrounded by high-rise commercial buildings in the central business district in Singapore, focusing on the effect of height-to-width ratio (H/W) on outdoor thermal comfort. The microclimatic parameters of different H/W scenarios were determined by ENVI-met numerical simulation. Field measurement was conducted to validate the results from the numerical simulation and they were in good agreement. The physiologically equivalent temperature (PET) was utilized as the thermal index to assess outdoor thermal comfort. It has been approved quantitatively that shading provided by high aspect ratios can improve outdoor thermal comfort in urban streets and H/W of 3 can be considered as a threshold with respect to outdoor thermal comfort in Singapore.


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*Keywords:* Thermal comfort; Urban environments; Physiologically equivalent temperature; Height to width ratio

## 1. Introduction

Urban environment is deteriorating in many tropical cities like Singapore due to rapid urbanization. The increased intensity of urban heat island (UHI) puts additional stress on the urban ecosystem and has implications for urban climate, air quality, and energy use for air conditioning, thus adversely affecting human well-being. The creation of thermally comfortable urban environments is very important for the participation of outdoor activities and also

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reduces the cooling energy consumption in buildings. An urban environment can be described as an amalgamation of buildings, vegetation, water bodies and some other factors. It is of significance to understand how human thermal comfort is influenced by these factors in the urban environment.

In recent years, urban microclimate and outdoor thermal comfort have gained increasing attention in the urban design and planning process. Some studies focused on urban microclimate modeling using computational fluid dynamics (CFD) simulations [1-6]. Other studies provided quantitative information on the effect of urban design on various microclimate variables like air temperature [7] and surface temperature [8]. These studies have provided valuable information on understanding the effect of urban microclimate on human thermal comfort in urban spaces. However, research that quantifies the possible effects of different urban design strategies on outdoor thermal environment is still lacking in Singapore.

As a result, this study intends to investigate outdoor thermal comfort in high-rise urban environments in Singapore and explore ways to improve thermal comfort in urban environments, focusing on the effect of height to width ratio (H/W) on outdoor thermal comfort.

## 2. Method

The methodology used in this study is a combination of experimental, numerical and analytical approaches. First field measurements were undertaken to obtain data for microclimate parameters. Then numerical simulation was carried out to simulate the microclimate from which the effect of urban design variables on microclimate and ultimately the thermal comfort index are calculated and analyzed.

### *2.1. Study area*

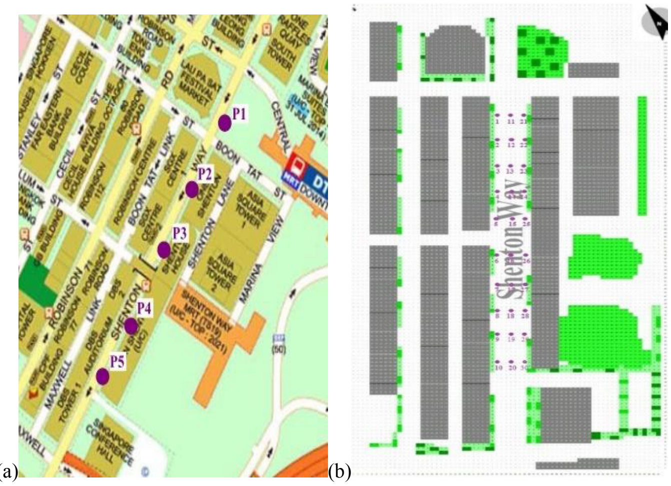
The study area is selected based on the following criteria: the representative of Central Business District (CBD), combination of traffic roads and pedestrian walkways, combination of areas both shaded and exposed to the sun, and flexibility to place the instruments. Based on these criteria, Shenton Way was selected as the case study for this research. The study area is a part of Shenton Way, which is a one way street in Singapore's central business district. The street is made of asphalt and 30m wide. The buildings along the street have different height from 4 to 50 storeys, which is from 20m to 235m. The canyon axis is oriented in the direction of NE-SW. Some sparse vegetation along the street is noticeable.

### *2.2. Field measurement*

Field measurement was conducted at Shenton Way from 1 March to 31 May 2012. The measurement points were chosen in order to represent the whole study area and located in between the traffic road and pedestrian walkway. Five measurement points along Shenton Way were stationed as shown in Fig. 1(a).

### *2.3. Numerical simulation*

The simulation study by ENVI-met numerical modelling was carried out on 27 April 2012 since it is the hottest day during the measurement period, according to meteorological data from Sentosa weather station near the study area. The model was simulated for 18 h starting at 4am and ending at 10pm. The best time to start the simulation is in the night or at sunrise so that the calculation can follow the atmospheric processes [9]. ENVI-met model was constructed according to the actual conditions of the study area. The model domain (base case) for the study area is shown in Fig.1 (b).




(a) (b)

Fig. 1. (a) Field measurement points at Shenton Way; (b) Model domain for the study area.

### 2.4. Outdoor thermal comfort assessment

In order to analyze the effect of street aspect ratios on outdoor thermal comfort, five alternative design scenarios (H/W=1, 2, 3, 4 and 5) were simulated by ENVI-met 3.1 and compared with the base case.

For the outdoor thermal comfort assessment, physiologically equivalent temperature (PET) was employed in this study as the thermal comfort index. PET has been widely used for outdoor thermal assessment [10-14], and it has been adopted by the German guidelines for urban and regional planners. PET was calculated using the RayMan model [4, 15]. It can be easily estimated by air temperature, relative humidity, wind speed, mean radiant temperature, clothing and activity level of people. When running PET with RayMan model it assumes 0.9 clo for clothing level and 80 W for activity level [4, 15].

In order to compare PET between different street design scenarios, 30 points were extracted from the study area for the thermal comfort analysis as shown in Fig.1 (b). These extracted points can represent a complete survey of the thermal comfort conditions of the study area and differentiate the edges and the center. The 30 points were placed in the model as receptors so that the microclimate variables needed for thermal comfort analysis can be automatically exported by simulation modelling. The height was 2.0m above the ground for all the extracted points.

## 3. Results

### 3.1. Validation of ENVI-met simulation

The measured data from field measurement on microclimate parameters were compared with the result generated by ENVI-met simulation (base case). The comparison also helps to understand the strength and limitations of ENVI-met. Once validated ENVI-met simulation was then applied to evaluate the outdoor thermal comfort.

The hourly-based metrological parameters including air temperature, relative humidity, wind speed and globe temperature on 27 April 2012 were extracted from field measurement database to validate the ENVI-met simulation. Table 1 shows the simulated and measured results at 3pm for different microclimatic parameters. It can be seen that results from numerical simulation and field measurement were in good agreement. In this paper, the comparison of different street design scenarios was based on 3pm because 3pm was the hottest time according to the measurement and simulation results.

Table 1. Simulated and measured difference of different microclimatic parameters at 3pm.

| Point | Air temperature difference | Mean radiant temperature difference | Wind speed difference | Relative humidity difference |
|---|---|---|---|---|
| P1 | -0.66 | +4.92 | 0 | - |
| P2 | -0.01 | - | - | -0.14 |
| P3 | -0.42 | +4.53 | +0.14 | - |
| P4 | -0.40 | - | - | +0.76 |
| P5 | -0.03 | +4.37 | +0.24 | - |

### *3.2. The effect of H/W on microclimate*

The air temperature patterns for the base case and the five alternative design scenarios at 3pm are presented in Fig. 2. It is clear that deep streets have lower air temperatures than shallow streets. The maximum air temperature difference between the different scenarios is up to 0.80ºC. It can also be seen that air temperature stops decreasing when H/W reaches 4 and design scenarios with H/W of 4 and 5 have identical air temperature distributions.

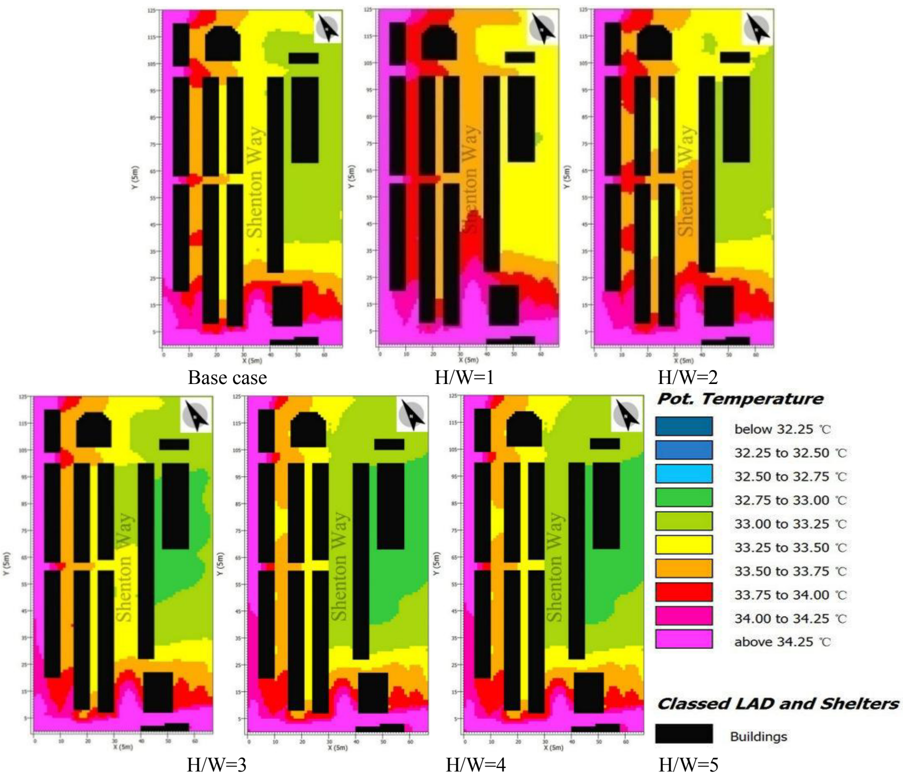



Fig. 2. Air temperature for different aspect ratios.

Fig.3 shows the mean radiant temperature for the base case and the five alternative design scenarios at 3pm. Like the air temperature, the mean radiant temperature decreases with increasing H/W. The differences can exceed 30ºC for different height-to-width ratios. However, no differences can be observed when H/W reaches 3. It can also be observed that places with less shading or no shading (i.e., the right part of the modeled area) have much higher mean radiant temperatures than other places.

As for the wind speed and relative humidity, no distinct differences can be found between different design scenarios.

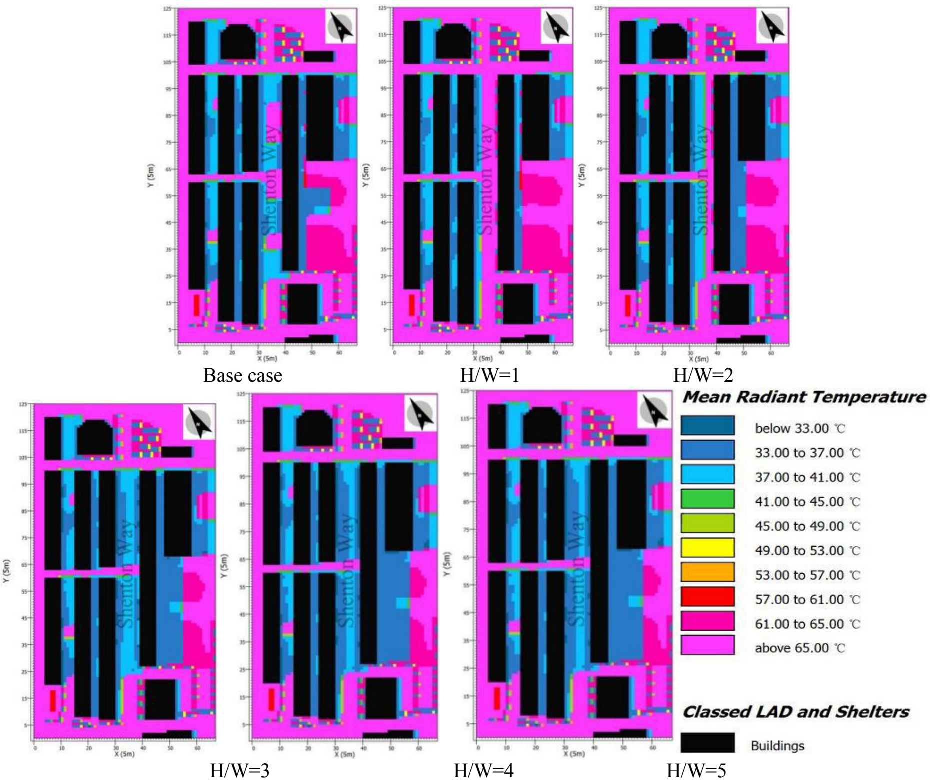



Fig. 3. Mean radiant temperature for different aspect ratios.

### 3.3. The effect of H/W on outdoor thermal comfort

Physiologically equivalent temperature (PET) was employed in this study as the thermal index for thermal comfort evaluation. As mentioned before, in order to evaluate outdoor thermal comfort for different design scenarios, 30 points were extracted from the study area. For the purpose of illustration, these 30 points are grouped into 18 points based on the similarity of the location. The PET values of the 18 representative points for the six design scenarios at 3pm are presented in Fig.4.

It can be seen that PET decreases with the increase of H/W, which indicates that deep streets has better thermal comfort conditions than shallow streets. The PET difference between deep and shallow canyon can be more than 20°C. However, the improvement of thermal comfort is not obvious when H/W reaches 3. Thus, H/W of 3 can be considered as a threshold for outdoor thermal comfort, since the global radiation received by the street varies little for height-to-width ratios larger than 3. It can also be seen in Fig.4 that the left part (Point 1 to 10) of the street has lower PET values than the middle (Point 11 to 20) and right part (Point 21 to 30) for all the design scenarios. This is because all the scenarios discussed here have the same street orientation (NE-SW), which provides good shading to the left part of the street in the afternoon.

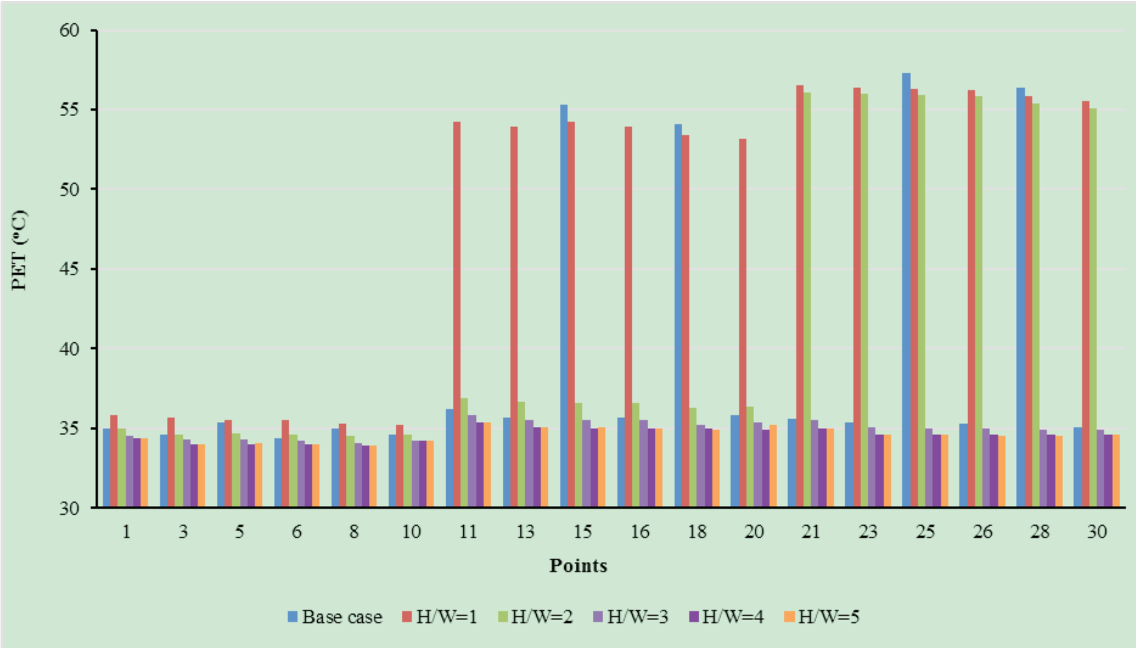



Fig.4. PET value for different aspect ratios.

## 4. Discussion

The above results suggest that thermal comfort is difficult to achieve naturally for the given setting of the study area at 3pm (PET>35ºC) but can be achieved by appropriate street design strategies. Shading is the key strategy for promoting outdoor thermal comfort in Singapore because it leads to a reduction of air temperature and mean radiant temperature and hence to a cooler thermal sensation.

It has been pointed out that urban shading at street level is a function of street orientation as well as building height and density (H/W ratio) [16]. Shading achieved by means of high aspect ratios can reduce substantially the thermal discomfort of people at street level. The PET value in a deep canyon could be 20ºC lower than that in a shallow canyon at the same time. H/W of 3 could be considered as a threshold for outdoor thermal comfort in urban streets in Singapore. It would be better if additional shading devices, particularly horizontal devices, are provided for shading.

## 5. Conclusions

The effect of height to width ratio (H/W) on outdoor thermal comfort in high-rise urban environments in Singapore was analyzed in this paper. ENVI-met was employed to numerically simulate the microclimate within the street canyon. Field measurement was also carried out to validate ENVI-met simulation results. The results show that shading is the key strategy for improving outdoor thermal environment in Singapore because it leads to reduction on the air temperature and mean radiant temperature simultaneously. Shading achieved by means of high aspect ratios can improve thermal environment at street level. The paper concludes that H/W of 3 can be considered as a threshold with respect to outdoor thermal comfort in Singapore.

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